Crosswell seismic imaging in three dimensions

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Summary

The simultaneous acquisition of multiple profile, high-resolution datasets from highly deviated or horizontal wells is the new crosswell seismic frontier. These datasets have motivated development of a 3D modeling approach that is consistent "from the ground up", an altogether different approach than interpolating 2D results. For several reasons, we believe it is more desirable to develop new modeling and processing techniques than to extend the typical 2D methods into 3D.

We have developed an efficient means of integrated 3D interwell imaging that we term a "common earth model". The model formulation consists of closely spaced (~2 m.) 3D surfaces which mimic structural contours, and a series of 2D velocity functions between each layer. Both the surfaces and the velocity functions are represented by Chebyshev polynomials, and hence any spatial derivatives required for both the ray tracing and traveltime inversion can be determined analytically in closed form. The velocity inversion algorithm is well determined while still providing high spatial resolution. An additional algorithmic advantage of our formulation is the "natural" application of continuation constraints to regularize the traveltime inversion and increase spatial resolution (after Bube and Langan, 1994).

Introduction

The decreasing cost of obtaining high-resolution multiple profile crosswell data stimulates the development of 3D imaging techniques that simultaneously employ consistent model constraints across an entire volume. Traditional 2D inversion techniques have proven very useful in mapping subsurface structures between two wells (Lazaratos and Marion, 1997), but often fail to match crossline ties in the case of overlapping profiles. "Crossline" consistency from the ground up is preferable to interpolation. Furthermore, the usual methods of velocity parameterization in 2D, nodal models consisting of a number of cells, are too bulky and underdetermined for sufficiently detailed 3D inversion of crosswell data. We identify three things we find essential for 3D crosswell interwell imaging:

1. Model consistency across the volume for all profiles
2. Velocity parameterization sufficiently general for detailed resolution
3. Inversion parameters as well determined as possible

The common earth model we describe below efficiently satisfies these criteria. This model also provides a natural means of employing continuation constraints for the velocity inversion which have been shown to dramatically increase the spatial resolution of traveltime velocity inversion (Bube and Langan, 1994).

Common Earth Model

Items two and three from the list above require a model formulation with as few parameters as possible. This goal and the aim of consistency throughout the volume are elegantly satisfied by the use of Chebyshev polynomials. The models consist of Chebyshev surfaces spaced vertically on the order of two meters, with a 2D slowness field specified within each layer. The slowness field is parameterized with Chebyshev polynomials, and traveltimes for straight ray segments between each surface are calculated by line integrals involving these polynomials. Figure 1 shows a schematic of the model geometry.

Model surfaces are fit to the real data of "horizon picks" from well logs. For each of a set of wells, a pick is made on the tops of common horizons. The coefficients of the polynomials are found by SVD of this data. It is possible to fit surfaces of up to third order by weighting the energy of the various coefficients. Figure 2 shows an example of surfaces fit to horizon picks from a series of five deviated wells in Chevron's Buena Vista Hills field in Kern County, California (Langan, et. al., 1998, Crosswell seismic imaging in the Buena Vista Hills, San Joaquin Valley: a case history).

It can be seen from Figure 2 that weighting the energy of the various coefficients is a direct means of spatial smoothing. Weighting the coefficients is also a natural means of employing continuation constraints on the velocity inversion (discussed in more detail below).

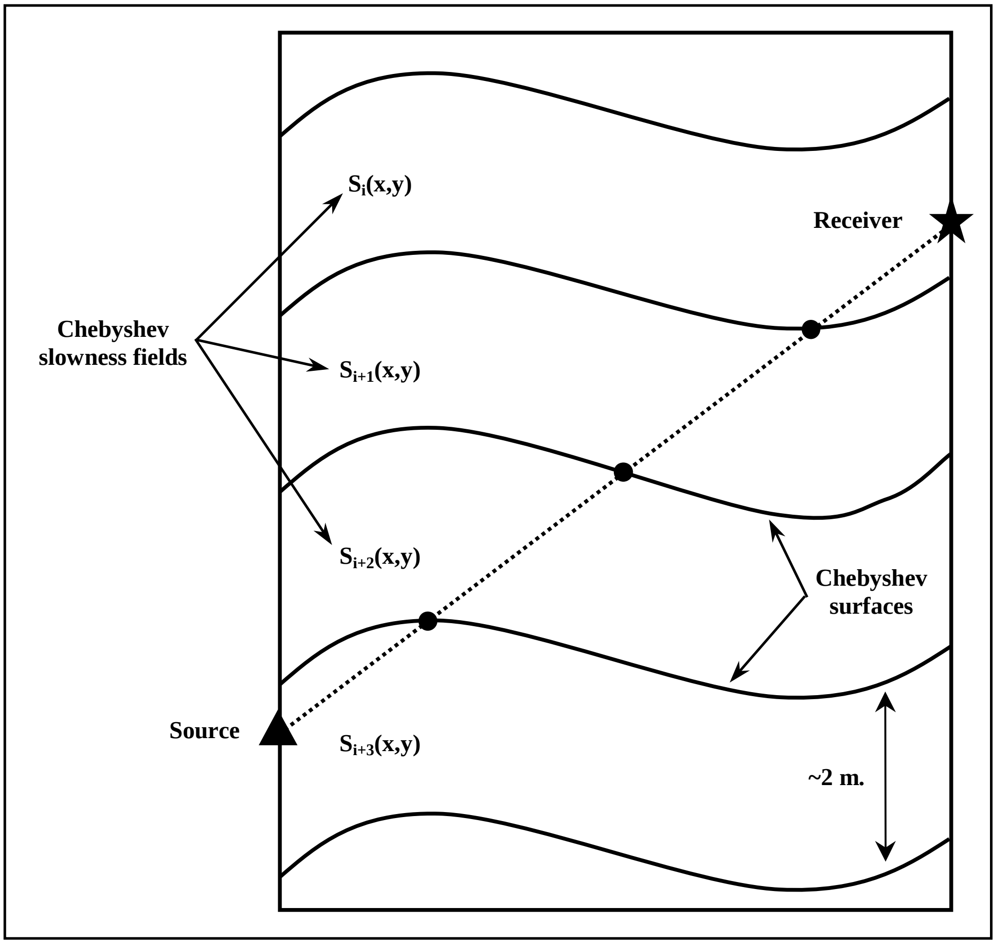

Figure 1: Schematic of common earth model parameterization.

Raytracing

The specification of the common earth model via Chebyshev polynomials introduces several key advantages. The explicit form of the polynomials can be exploited for determination of spatial derivatives, and the polynomials are continuous and continuously differentiable throughout the model. This significantly improves stability and convergence for the forward problem of modeling traveltimes compared to traditional raytracing algorithms. We find that the raypath optimization is extremely stable and will rapidly converge to paths satisfying Fermat's principle of least time. Raypaths can be found for arbitrary model specification, and subject to the model constraints, they will be accurate in that any deviation from the solution raypath will result in increased traveltime.

Velocity Inversion and Continuation Constraints

The only derivatives required for the velocity inversion are the partials of traveltime with respect to changing the coefficients of the slowness polynomials. We again exploit the polynomial formulation for determination of these derivatives in closed form.

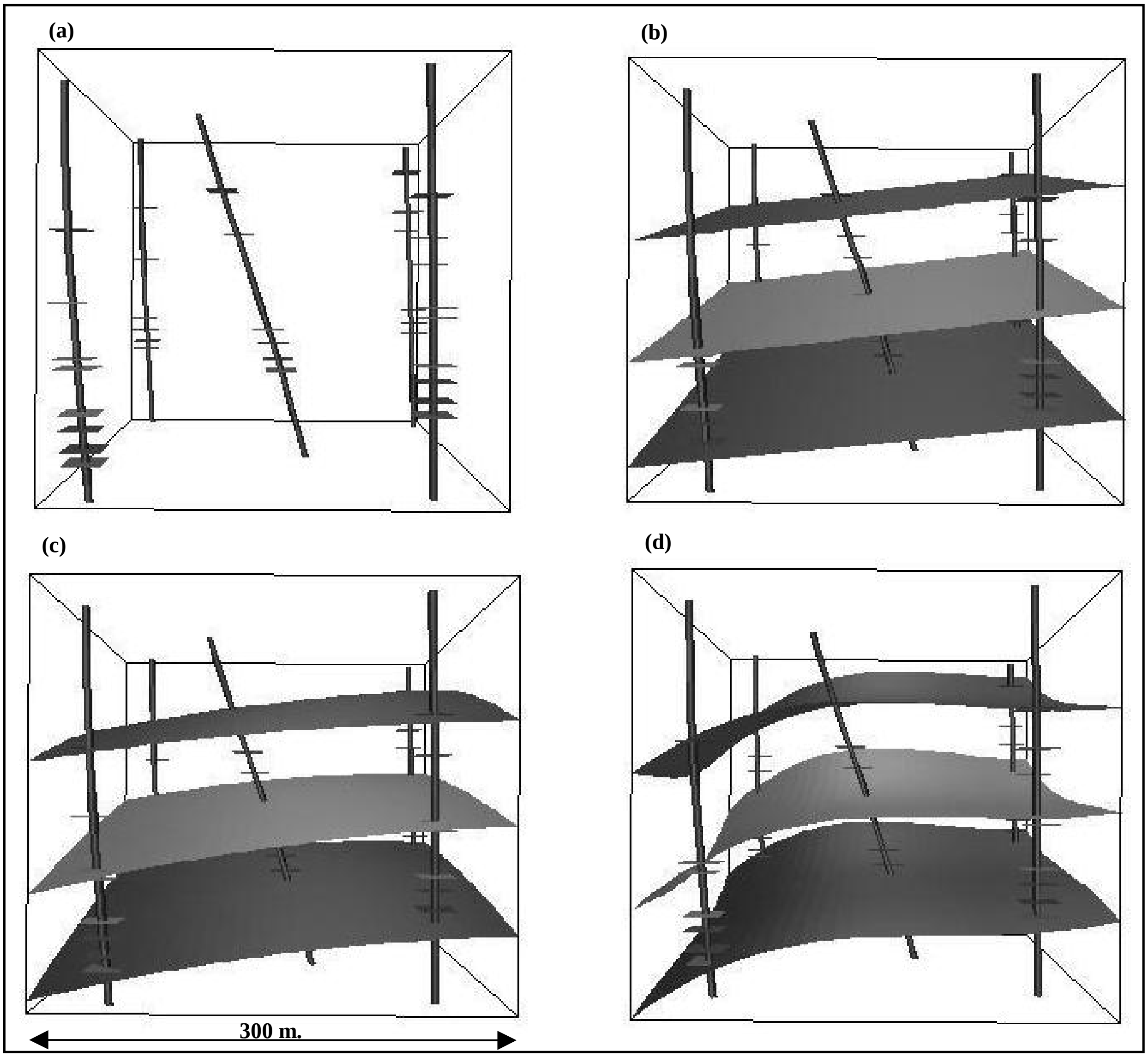

Figure 2: Chebyshev surfaces fit to common horizon picks for Chevron's Buena Vista Hills geometry.

(a) "Horizon picks" from well-logs.
(b) First-order surfaces fit to horizon picks.
(c) Second-order surfaces fit to horizon picks.
(d) Third-order surfaces fit to horizon picks.

Using continuation constraints in velocity inversion significantly improves resolution. Bube and Langan (1994) introduce an inversion scheme that resolves long-wavelength features first, and successively increases spatial resolution in the model (generally by decreasing the penalty weights for constraints on vertical and horizontal smoothness in a regularized inversion). This approach is shown to more accurately reach a global residual minimum, and to reduce model-matching errors for synthetic datasets to well below the threshold established by unconstrained inversion.

Clearly, continuation constraints can be very naturally applied to the Chebyshev formulation for velocity parameterization used in the common earth model introduced here. Inverting only for the zero-order term resolves first the longest horizontal wavelength features (the layer constants or 1D with depth model). Successively adding energy to the higher orders of the polynomials increases the spatial resolution of the velocity field. The slowness fields used in our model formulation can be represented by Chebyshev polynomials of arbitrary order. A separate local minimum will be found for each pass, inverting finally for the complete n^{th}-order polynomial.

The inversion of crosswell traveltime data is “constrained” by the parameterization of our common earth model. Using the *a priori* information of the tops of the horizon picks from well logs, the model is constrained by the specification of the surfaces that are fit to the horizon picks. This has the effect of greatly increasing vertical resolution (compared to pixelized models) by imposing sharp vertical boundaries. Vertical resolution then becomes a fraction of the interwell Fresnel zone.

In addition to satisfying the vertical boundaries, velocity fields are constrained by the polynomial representation. The primary effect is to greatly reduce the number of inversion parameters as compared to a pixelized model. Consequently, each layer that has at least ten raypaths is even-determined.

Conclusions

The common earth model introduced here is a new technique for inversion of multiple profile, simultaneous 3D crosswell data. This method extends interwell imaging into datasets acquired from highly deviated or horizontal wells in areas of complex structure. The common earth model introduces constraints that greatly increase spatial resolution and pose a much better determined inverse problem than typical 2D crosswell models. The use of Chebyshev polynomials allows calculation of the spatial derivatives required for both the raypath and velocity inversion to be determined analytically in closed form. The model formulation also very naturally allows for the application of continuation constraints. Finally, exact determination of the partials required for the ray bending results in speedy and efficient forward modeling of traveltimes for a given velocity model.

Presentation of this material will demonstrate application of the common earth model introduced here to real datasets, both 2D and 3D, and include more details of implementation.

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